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Boron carbide based solid state neutron detectors: The effects of bias and time constant on detection efficiency

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Abstract

Neutron detection in thick boron carbide(BC)/n-type Si heterojunction diodes shows a threefold increase in efficiency with applied bias and longer time constants. The improved efficiencies resulting from long time constants have been conclusively linked to the much longer charge collection times in the BC layer. Neutron detection signals from both the p-type BC layer and the n-type Si side of the heterojunction diode are observed, with comparable efficiencies. Collectively, these provide strong evidence that the semiconducting BC layer plays an active role in neutron detection, both in neutron capture and in charge generation and collection.

1. Introduction

The development of efficient solid state neutron detectors is hampered by the transparency of most materials to the passage of neutrons. Few elements possess a significant capture cross section for thermal neutrons, and among these elements, those suitable for forming a semiconducting solid are rare indeed. Boron is uniquely suitable, having a large capture cross section for thermal neutrons, generating high energy ions that are easily detectable on neutron capture and forming a boron rich semiconducting solid, boron carbide (BC) [1, 2], grown by plasma enhanced chemical vapor deposition (PECVD). The growth and properties of a semiconducting form of BC have been intensively studied for the last 20 years, resulting in heterojunction and homojunction diodes [1, 3–7], Esaki tunnel diodes [8], and, most relevant for this manuscript, solid state neutron detectors [2, 9].

These solid state neutron detectors are quite distinct from conversion layer detectors, in which neutron capture coatings are grown on semiconducting materials. In such conversion layer detectors, ⁶Li, ¹⁰B, ¹¹³Cd and ¹⁵⁷Gd have been used to capture the neutrons resulting in secondary particles that are transferred to the semiconducting charge capture layers

[10–13]; these neutron detectors suffer from self-absorption effects [12] leading to low attainable efficiencies. Semiconducting BC circumvents these restrictions by combining both neutron absorption and charge capture in the same material, leading to much higher attainable efficiencies.

The neutron capture reaction with ¹⁰B is well known

and results in the ejection of highly energetic ions that generate large numbers of electron–hole pairs in a semiconductor. Naturally occurring boron contains 19% ¹⁰B; for a fully enriched thin film of BC, 50% neutron capture efficiencies are attainable at a thickness of 20 μm [14]. Unlike conversion layer detectors in which neutron absorption effects limit the ultimate attainable efficiency to ~10–15%, calculated neutron capture efficiencies in BC based diodes scale with thickness; however, the overall detection efficiency is highly dependent on the charge capture efficiency in *both* semiconductors. As the thickness of the BC layer is increased, the semiconducting properties of the BC layer assume increased importance.

This fundamental difference between the two types of detectors leads to differing efficiencies, pulse height signatures and detection thresholds as shown both in GEANT4 Monte Carlo simulations [15] and a simple physical model [14, 15]. There are two striking differences—the models indicate that for a BC/Si diode, the energy deposition spectra are weighted to higher energies, with a cut-off below the lowest energy signature at 0.84 MeV, whereas in the BC conversion layer, the pulse height spectra are weighted towards lower energies with a cut-off at the highest energy of 1.78 MeV. In both cases, a thickness of 1 μm BC leads to a substantial smearing of the individual peaks associated with the ^4He and ^7Li ions. In addition, in the case of the diode detector, peaks at the summed energies of the ^7Li and ^4He ion should be present, an effect absent in the case of a conversion layer detector since charge capture and neutron capture occur in two different layers. Both predictions are modified in the presence of electronic and statistical noise and both depend on the assumption of 100% charge capture, an assumption we will show is highly dependent on the parameters of the associated processing electronics and the properties of the semiconductor.

In *thin* BC/Si heterojunctions, much of the charge capture occurs in the Si layer due to geometrical constraints, and hence the neutron detection signatures are very similar to those of conversion layer detectors. Measurements on a 232 nm thick BC/n-type Si heterojunction diode [2] resulted in an efficiency of 3.35×10^{-3} , even at zero applied bias, almost exactly equal to the calculated neutron capture efficiency. The effect of increasing the bias led to small increases in the detection efficiency of less than 10%, because such a large amount of charge is liberated on neutron capture, that capturing even small fractions of it leads to a charge pulse above threshold noise [2]. Subsequent efforts on neutron detection in BC/Si heterojunction diodes have focused on the parameters important for increased efficiency. Although increasing the thickness of the BC layer must increase the neutron capture rate, the entire process from neutron capture to charge collection (in both the BC and the Si) and the subsequent pulse processing are found to play important roles in the overall detection efficiency.

In this paper, we describe neutron detection experiments on thick (1.0 μm and 1.8 μm) layers of BC on n-type Si. This five to nine fold increase in thickness over previous samples leads to a greater proportion of charge being captured in the semiconducting BC layer, resulting in a larger dependence on the properties of the BC in the neutron detection efficiencies. As we demonstrate below, the charge pulse rise time is governed by the characteristics of the semiconducting material and is substantially different for the two materials. Both the applied bias voltage and the integration time constants are shown to lead to much improved detection efficiencies.

The neutron capture reaction in the BC/Si heterojunction detector for thermal neutrons is described in equation (1) and illustrated in figure 1. Neutron capture occurs *only* in the p-type BC side, with the neutron capture site serving as the origin for highly energetic ^7Li and ^4He ions, emitted back-to-back. Electron-hole pairs are generated by the passage of these secondary ions through the semiconductor. The signal at either

electrode arises mainly from charges generated within the depletion layer. The charge carriers are accelerated due to the internal electric field, with negative (positive) charge drifting towards the positive (negative) electrode. Depending on the ground and center pin connection of the coaxial cable, the charge pulse consists either of electrons (from the Si side) or holes (from the BC side). Hence the charge pulse we collect consists of only one type of charge. Since the mobility of carriers on the BC and Si side differ vastly, the choice of time constants has a significant impact on the charge collection, and consequently on the neutron detection efficiency. We will show that there is a significant difference in the signal, depending on whether electrons or holes are collected at the center pin.

2. Experimental details

The 1.0 μm and 1.8 μm BC layer were grown using PECVD from an orthocarborene closo-1,2-dicarbado-dodecaborane ($\text{C}_2\text{B}_{10}\text{H}_{12}$) precursor [16] on n-type Si(1 1 1) substrates (resistivity $\sim 100 \Omega \text{ cm}$) in a custom designed parallel plate 13.56 MHz rf PECVD reactor [1]. The base pressure was $5.3 \times 10^{-5} \text{ Pa}$ and the working pressure was 27 Pa Ar gas. The substrate temperature was held at 330 $^\circ\text{C}$ during the deposition with 30 W rf-power supplied. The film growth rate, 80 nm/10 min, was obtained by *ex situ* grazing incidence x-ray reflectivity. Ohmic contacts for BC and Si layers were sputter deposited using Cr and Au metal targets [1] with contact areas ranging in size from 0.785 to 19.625 mm^2 on the BC side. The Si side contacts covered the entire area of the chip, $\sim 1 \text{ cm}^2$.

The neutron source used is a Thermo Electron Corporation MP320 [17]. The $1.0 \times 10^8 \text{ n s}^{-1}$ fluence of high energy 14 MeV neutrons is moderated using a 10 cm thick beryllium block followed by 8 cm of paraffin. The thermal neutron fluence rate ($3.0 \times 10^3 \text{ n cm}^{-2} \text{ s}^{-1}$) was determined using a ^3He detector [18]. Each pulse height spectrum was obtained from a total incident neutron count of $\sim 423,900$ for the 1.0 μm , and $\sim 1,356,480$ for the 1.8 μm neutron detector. A coaxial cable connects the detector to a Canberra 2004 charge-to-voltage preamplifier and subsequently to a Canberra Digital Signal Processor (DSP 9600) for pulse counting. The outer shield of the coaxial cable is grounded and connected to either the p or n side of the junction. The scope traces were obtained on a Tektronix TDS520D oscilloscope. Three different trapezoidal time constant filters were used to process the signal from the preamplifier. Background measurements were obtained using a 0.025 mm Cd foil, as a thermal neutron shield [19]. All experiments with and without Cd foil were performed under identical conditions of neutron flux and applied bias to obtain the most reliable measurement of background.

3. Semiconducting properties

Current-voltage (I - V) curves for both p-type BC/n-type Si heterojunction diodes are shown in figure 2. The low leakage currents are crucial in suppressing the noise peak, which enables the detection of neutron capture signals. The combination of low leakage current and large breakdown voltage ($< -40 \text{ V}$) allow for the application of large

Figure 1. (Top) A neutron capture event in a BC/Si heterojunction diode detector. (Diagram not to scale.) The charge sensitive preamplifier may be connected to either side of the junction, collecting either a hole or an electron current. (Bottom) Schematic diagram of the neutron detection system used showing the associated electronics. Oscilloscope traces taken directly after the preamplifier are dominated by the rise time associated with charge capture within the semiconductor whereas oscilloscope traces taken after the DSP are a convolution of the rise time with the selected time constant.

bias voltages, without significant increases in the noise level. This enhancement of the device properties for neutron detection was accomplished by more stable plasma control, low doped ($100 \, \Omega \, \text{cm}$) Si wafers and thick BC deposition.

The $1.0 \, \mu\text{m}$ BC layer with a contact area of $0.785 \, \text{mm}^2$ and a leakage current of $0.098 \, \mu\text{A}$ (corresponding to a current density of $12.5 \, \mu\text{A} \, \text{cm}^{-2}$) at an applied bias of $-19 \, \text{V}$ shows a 10^3 fold decrease in the leakage current compared with the

Figure 2. I - V curves of (a) $1.0 \, \mu\text{m}$ BC and (b) $1.8 \, \mu\text{m}$ BC heterojunction diodes on n-type Si at room temperature. Inset (a): C - V curve for the $1.0 \, \mu\text{m}$ BC heterojunction detector showing the $V^{-1/2}$ dependence of the capacitance. Both I - V and C - V curves indicate a built-in voltage of $0.7 \, \text{V}$.

thin BC diode used in previous work [2]. In the case of the $1.8\ \mu\text{m}$ BC layer, we were able to utilize a much larger detection area ($3.14\ \text{mm}^2$) due to the higher resistance of the thicker film. The leakage current at $-19\ \text{V}$ corresponds in this case to $0.244\ \mu\text{A}$, leading to a much lower current density of $3.4\ \mu\text{A cm}^{-2}$. Both the $1.0\ \mu\text{m}$ and $1.8\ \mu\text{m}$ samples showed the same built-in potential, $V_{\text{bi}} = 0.7\ \text{V}$.

In a diode detector, the active region for charge capture is the depletion region, where charge recombination is highly suppressed. The depletion region increases with increasing reverse bias as expected, shown in the capacitance–voltage (C – V) measurement in the inset of figure 2(a), with the $V^{-1/2}$ dependence expected for a step junction [20]. The C – V curve indicates that the device is not entirely depleted over the range of bias used for neutron detection measurements (from 0 to $-19\ \text{V}$). In order to estimate the individual depletion widths in the BC (where the doping density is not well known) and Si, we first assume that at reverse biases $< -10\ \text{V}$, the BC region is fully depleted and the slope of the C^2 versus $1/(V_{\text{bi}} - V_{\text{appl}})$ line is entirely due to increasing depletion in the Si. From this we obtain a doping density of $4.5 \times 10^{12}\ \text{cm}^{-3}$ in BC, corresponding to a depletion width of $10\ \mu\text{m}$ at zero bias, well above the thickness of either of the two BC films. Hence over the entire bias range, the BC is always fully depleted. Application of a reverse bias leads to an increase in the depletion width on the Si side of the heterojunction, as well as increasing the internal electric field, both of which have implications for charge collection. Previous measurements of the resistivity of BC range from 10^8 to $10^{10}\ \Omega\ \text{cm}$ leading to a mobility ranging from 1.4×10^{-4} to $1.4 \times 10^{-2}\ \text{cm}^2\ \text{V}^{-1}\ \text{s}^{-1}$, many orders of magnitude lower than the mobility of the n-type Si ($1400\ \text{cm}^2\ \text{V}^{-1}\ \text{s}^{-1}$). This drastically lowered mobility has a pronounced effect on the charge capture efficiency.

4. Pulse height spectra

Neutron detection pulse height spectra with and without Cd foil are shown in figures 3 and 4 as functions of applied bias and integration time constants, respectively, for both the $1.0\ \mu\text{m}$ and $1.8\ \mu\text{m}$ diodes. All data shown in these figures were collected from the Si n-type side of the heterojunction diode, with the BC side grounded, and hence correspond to electron collection. Four bias voltages (figure 3) using the longest time constant with a $28\ \mu\text{s}$ rise and fall time and a $3.0\ \mu\text{s}$ flattop time, abbreviated as $28_3.0\ \mu\text{s}$, and three different trapezoidal time constants (figure 4) at a fixed bias voltage are shown. The smaller detection area of $0.785\ \text{mm}^2$ for the $1.0\ \mu\text{m}$ film leads to much lower count rates and less well-defined peaks. The details of the trapezoidal time constants are indicated in figure 4(c).

The pulse height spectra for the larger area $1.8\ \mu\text{m}$ thick detector show three peaks corresponding to the $0.84\ \text{MeV}$ ^7Li ions (first peak), $1.47\ \text{MeV}$ ^4He ions (second peak) and $1.78\ \text{MeV}$ ^4He ions (much smaller third peak). At $0\ \text{V}$, part of the $0.84\ \text{MeV}$ peak is subsumed within the noise peak but is clearly discernible at an applied reverse bias of $10\ \text{V}$. The low intensity of the $1.78\ \text{MeV}$ peak arises from the much lower probability (6%) of the reaction generating the $1.78\ \text{MeV}$ ^4He ions. A peak from

the $1.02\ \text{MeV}$ ^7Li ions is not distinguishable within our energy resolution but may be embedded within the first peak.

4.1. Effects of increased bias

With increasing applied bias, the pulse height spectrum broadens, and shifts to higher channel numbers, an effect also seen in earlier work on thinner detectors [2]. The secondary ions produced as a result of neutron capture within the BC layer are emitted with equal probability in all directions with path lengths of a few micrometers in both the BC and the Si (the path lengths are not identical). The amount of energy lost by the ions within the diode, varies from a minimum (when the ions are emitted normal to the film plane) to maximum (when the ions are emitted parallel to the plane of the sample) and corresponds to the number of electron–hole pairs produced. An increase in the applied bias results in increases in both the depletion width, which allows for charge collection over a larger region, and the internal electric field, resulting in higher accelerations and less charge trapping and recombination, both of which result in higher charge collection and hence higher channel numbers. The broadening of the pulse height peaks is also ascribed to increases in the depletion width, because charge may be collected from a much larger range of solid angles, resulting in a wider range of energies deposited.

A quantitative measure of the shift in the pulse height spectra with increasing bias may be obtained by using the second peak of the $1.8\ \mu\text{m}$ film. A plot of the peak position versus the bias across the depletion width (figure 5) shows a $(V_{\text{bi}} - V_{\text{appl}})^{1/2}$ dependence, similar to that of the C – V curve, further suggesting that as the depletion width (or reverse bias) increases, the fraction of charge collected increases proportionately. The peak position approaches, but does not reach saturation even at $20\ \text{V}$; and since the device is not entirely depleted, we may assume that applying still higher bias voltages would lead to increased charge collection. Because the range of the ^4He ion in Si is $5\ \mu\text{m}$ [19] and because all ions must originate in the BC layer, increasing the depletion width beyond $5\ \mu\text{m}$ in Si (reached at a bias voltage of $2.3\ \text{V}$) should lead to no further increase in the charge collection. The increases in peak position at biases $> 2.3\ \text{V}$ must result from increased acceleration of charge on both sides of the junction.

However, as will be discussed in figure 8, this does not correspond to increases in efficiency. Unlike in solid state gamma and x-ray detectors [19] the position of the peaks in the pulse height spectra provides no information about the neutron energy and energy resolution is not important; rather it is the intrinsic efficiency that must be maximized. For a particular neutron capture event, incomplete charge capture will still lead to a neutron count provided the signal-to-noise ratio is large enough.

4.2. Time constant

The time constant of the digital signal processor has a pronounced effect on the pulse height spectra and the neutron detection efficiency, showing higher efficiency at larger time constant. With increased time constant, the peaks become

Figure 3. Pulse height spectra as a function of reverse bias voltage with (○) and without (●) Cd foil on **(a)** a 1.0 μm BC and **(b)** a 1.8 μm BC/Si heterojunction detector, both with a trapezoidal time constant of 28_3.0 μs . Four different bias voltages are shown. The arrow points to the peak from the 1.47 MeV ^4He ion.

broader and shift to (slightly) higher channel number implying that with longer time constants larger fractions of the charge contribute to the pulse height spectra. The effect is most pronounced in going from the shortest time constant of 0.4_0.1 μs to the 12_1.6 μs time constant. This is consistent with earlier observations of a long rise time of $\sim 20 \mu\text{s}$ for charge pulses within the BC layer [2], compared with the $< 20 \text{ ns}$ rise time for the signal from the Si layer. This large difference in rise times presents an obstacle to obtaining ideal efficiencies because the signal processor may not recognize the long slow rise time signal from the BC as a peak, thereby ignoring the energy deposited in the BC.

These effects of the processing time constants are well described using both mathematical convolutions of the time constant with a model charge pulse as well as actual scope traces from the DSP (see figure 6). Since the output signal from the DSP is a convolution of the trapezoidal weighting function and the peaks from the BC and Si layers, the peak voltage for the integrated charge pulse determines the channel in the pulse height spectrum and the values of the time constant are key in determining this peak voltage. A time constant much shorter than the signal will lead to a deficiency in the peak voltage and may result in a signal that is subsumed in the noise channels, whereas too long a time constant will

Figure 4. Pulse height spectra as a function of time constant with (○) and without (●) Cd foil on (a) a 1.0 μm BC and (b) a 1.8 μm BC/Si heterojunction detector at 7 V and 5 V reverse bias, respectively. (c) Depicts the shape of the trapezoidal time constants for each case.

lead to a flat top in the DSP output and a subsequent saturation of the signal. A MATLAB [21] simulation, in which rectangular pulses with time durations corresponding to the expected charge collection times in the Si (20 ns) and BC (20 μs) layers, respectively, are mathematically convoluted with the appropriate time constants, is shown in figures 6(a) and (b). The area under each rectangular pulse is assumed to be the same, corresponding to equal amounts of total charge collected, an assumption we will show later to be erroneous. Black and red lines indicate the results of the convolution of the charge pulse from Si and from (Si + BC), respectively. The short 20 ns pulse from Si results in a voltage peak independent of the time filter, since the pulse duration is much shorter than the shortest time constant. The longer 20 μs pulse shows a significant (~75%) enhancement in the voltage peak with increased time constant. This simulation is for a particular *single* pulse in which the same amount of charge is liberated and collected in both the Si and the BC. The pulse height spectra are histograms of a large number of events that record the frequency of occurrence of the entire range of differing charge pulse heights, generated in the BC and Si. In general, for a single event, the charge pulses in the BC and the Si are

of different heights. However, it is reasonable to assume that on average the same amount of charge is generated in both (albeit with some small differences due to the differing path lengths of the ions and the depletion width in each.) With longer time constants and the resulting improved charge collection from the BC side, the entire pulse height spectra should be shifted to higher channel number by 75%. i.e. the same amount seen for a single pulse. This is not the case.

Scope traces of charge pulses taken after the DSP are shown in figures 6(c) and (d), using the short (0.4_1.0 μs) and long (24_3.0 μs) time constant, respectively, with the same applied bias of 5 V. The applied bias values are chosen so that the depletion width in the Si is roughly equal to the range of secondary ions in the Si. The output signals from the DSP are already processed using the chosen trapezoidal filter; allowing for an investigation of the effect of the time constant directly from these scope traces. An overlay of the convolution integral on the corresponding scope traces indicates excellent agreement as a function of time, the voltage heights having been scaled to match. Hence the discrepancy between the expected 75% increase in channel number and the experimentally obtained 13% increase must result from incomplete

Figure 5. (a) The channel number of the peak assigned to the 1.47 MeV ^4He ion in the $1.8 \mu\text{m}$ BC/Si heterojunction diode detector as a function of voltage across the depletion width, $|V_{bi} - V_{appl}|$ (filled circles), and time constant (unfilled squares). The dashed curve is a $(V_{bi} - V_{appl})^{1/2}$ fit. Charge collection increases in going from the $0.4_0.1 \mu\text{s}$ time constant to the $12_1.6 \mu\text{s}$ time constant and saturates thereafter, as expected from the $\sim 20 \mu\text{s}$ rise time of charge in the BC layer. **(b)** The noise peak channel as a function of bias voltage (squares) and time constant (triangles) with charge signal obtained from the n-side and at 0 V bias from the p-side (red circle). Increases in signal-to-noise are best achieved by increasing the time constant.

charge capture, most likely from the BC side. Since the entire calculated increase results wholly from the signal in the BC layer, a simple calculation indicates that the 13% increase implies that at most 20% of the charge generated in the BC layer is captured. Impurities and structural defects in the PECVD deposited BC, which is at best an imperfect crystal [22], hamper the charge transport process, trapping charge carriers into deep impurity levels and/or recombination centers leading to a loss of charge carriers [19].

The disparate charge collection times and efficiencies are also relevant in any discussion of the expected sum peak. The position of the sum peak in the pulse height spectra obtained from the Si side is complicated by the much lower charge collection in the BC semiconductor. A simple analysis of the sum peak for the more probable neutron capture reaction shows

that the peak will deviate substantially from its expected position. Assuming that only 20% of the charge liberated by the ^4He and ^7Li ions is captured within the BC layer, the sum peak position, rather than lying at the channel corresponding to 2.31 MeV, will instead be spread over channels ranging from a low of 0.46 MeV (for the rare event in which both ions are captured within the BC layer-note that this is well below the first ^7Li peak energy) to a high of 1.64 MeV (for events in which the ^4He ion traverses *only* the Si layer and the ^7Li ion traverses the BC layer, an event which occurs only for neutron capture at the BC/Si boundary). The substantial broadening and lowering of energy make it impossible to definitively identify the sum peak in the pulse height spectra. Any evidence of the sum peak will only be present as higher energy tailing of the ^4He peak and is subsumed within the less probable 1.78 MeV ^4He peak.

4.3. Noise and charge recombination

The pulse height spectrum for charge (hole) capture on the p-type BC side is shown in figure 7, together with oscilloscope traces, at 0 V applied bias. Two striking differences are apparent when compared with electron collection from the Si side of the junction. The noise and signal peak are shifted to lower channel number (corresponding to lower voltage pulse heights), and are extremely narrow. Correspondingly, the number of counts in the signal channel is significantly higher, with a peak height of ~ 600 counts (as compared with ~ 175 and 75 for the Li and He peaks, respectively, for charge collected from the Si side). The lowered noise level arises from better grounding on the Si side, due to the higher conductivity of Si as compared with BC. The neutron detection signal is peaked at channel 28, much lower than either the ^4He or ^7Li peak identified in the pulse height spectra collected from the Si side, a consequence of the loss of charge carriers within the BC layer. The identification of the peak is tricky. Assigning it to the 1.47 MeV ^4He peak, the peak position at channel 28 (compared with the peak position of channel 120 for collection on the Si side) is consistent with the low fraction of charge (20%) that we estimate for collection at the BC side electrode. However the 0.63% efficiency obtained is anomalously high, as in this scenario, all signal from the ^7Li ion is buried within the noise peak. If, instead the peak is assigned to overlapping ^7Li and ^4He peaks, then the increased efficiency from the BC side as compared with the Si side may be attributed to the lower noise level and hence greater collection of the lower energy ^7Li peak. In fact, the separation of the signal peak from the noise is similar to that seen for a much higher bias voltage of 10 V (figure 3(b)) for charge collection on the Si side, and the efficiency is similar (0.63% at 0 V for p-side and 0.65% at 10 V for n-side). The width of the peak, < 40 channels, is significantly lower than for charge collection on the Si side (> 200 channels). This is because, for charge collection on the Si side, charge that is generated in the BC layer is severely attenuated by charge capture and recombination, before reaching the Si layer, whereas the charge generated by the passage of ions through the Si layer is barely attenuated. Hence the

Figure 6. (From top to bottom) Two simulated charge pulses, one using a short rise time of 20 ns (as seen in Si) and the other using two rise times, one of 20 ns (for Si) and 20 μ s (for BC). The two trapezoidal time constants are illustrated in the second row. Outputs of the convolution integral between the charge pulse and the filter are shown in (a) and (b). Two scope traces taken from the same sample using the same reverse bias voltage of 5 V are shown in (c) and (d). The trace on the left is taken using a short time constant (0.4_0.1 μ s) and the trace on the right a long time constant (2.8_3.0 μ s). The convolution curves of (a) and (b) are scaled for height and then overlaid on the scope traces.

charge collected is distributed over a large range of channels, with the lowest channel number corresponding to charge production almost entirely within the BC layer and the highest channel number corresponding to charge production almost entirely within the Si layer. For collection on the BC side, however, all charges, whether generated in the BC or Si layer, must pass through the BC layer, being severely attenuated by charge capture and recombination. Hence, the spread in the charge pulse heights is small

The effects of increased bias voltage and time constant are summarized in figures 5 and 8. Figure 5 shows the channel

number shift with applied bias and time constant. Increased bias voltages shift both the signal and noise peaks to higher channel number, limiting the attainable efficiency using increased bias. Increasing the time constant has no effect on the noise peak position, but does show a small increase in the signal channel number that saturates at the 12_1.8 μ s time constant. The best signal-to-noise ratio, defined as the ratio of the pulse height channel numbers for the 0.84 MeV ^7Li and the 1.47 MeV ^4He peaks to the noise peak, is 5.8 and 13.2, respectively, at an applied bias of 17 V with the longest time constant.

Figure 7. Scope traces at the output of the preamplifier from (a) electron signals (from the n-type Si) and (b) hole signals (from the p-type BC). (c) and (d) Pulse height spectra for the 1.8 μm BC/n-Si detector with the center pin connected to the n-side (c) and the p-side (d) of the diode. All data shown are at 0 V bias using the longest time constant.

Figure 8. Neutron detection efficiencies as functions of reverse bias voltage and time constants for the 1.0 μm and the 1.8 μm BC/n-Si heterojunction diodes. The ideal efficiency is 0.80% for the 1.0 μm BC detector and 1.46% for the 1.8 μm BC detector. A relatively high efficiency from the p-side (brown square) is due to better grounding of the silicon side electrode as shown in figure 5.

5. Neutron detection efficiencies as functions of BC thickness, bias, and time constant

The detection efficiencies for thermal neutrons as functions of bias and time constants are obtained by taking the

difference between the total integrated detection counts above a chosen channel number (depending on the noise signal) with and without Cd foil and are shown in figure 8.

Below ~ 10 V, increases in applied bias lead to marked increases in the neutron detection efficiency. Above this value, there is little change in the efficiency although the pulse height spectra indicate increased charge collection, since as long as each neutron capture event leads to sufficient charge collection (i.e. above the noise level), further increases in charge collection lead to no increase in efficiency. At 0 V, the depletion width in the Si is 2.45 μm , comparable to the (totally depleted) 1.0–1.8 μm thickness of the BC and a greater fraction of the charge will arise from the BC layer, travelling through the depleted BC and into the Si. Hence at this low bias, the effect of increased time constant is most pronounced, due to the greater fraction of charge with the slow rise time associated with the low mobility of charges within the BC layer. As the bias increases, depletion on the Si side increases, leading to more efficient charge capture in the Si. These thick BC/Si heterojunction detectors show very high enhancement (almost 160% for the 1.0 μm BC layer at the shortest time constant) of the efficiencies with increased applied bias, quite different from the behavior reported in thin BC heterojunction detector [2], in which the efficiency increased by only 10%, presumably due to the increased charge capture within the much thicker BC layer.

The average time interval between consecutive incident neutrons for our experiments is 0.04 s and 0.01 s for the 1.0 μm and 1.8 μm detectors, respectively. The sum of the

rise and decay times for charge generation and capture is less than 0.0001 s for a single neutron capture event. Therefore, at <1% detection efficiency, the average time interval between successive incident neutrons is 4 orders of magnitude larger than the time duration of the voltage pulse from a single neutron detection event making pulse pile-up highly improbable. Neither detector showed any degradation in neutron detection efficiency over a period of 15 months.

6. Conclusions

The parameters necessary for the efficient operation of solid state BC/Si neutron detectors with micrometers-thick BC layers have been investigated. The novelty of such detectors requires the development of a fundamental understanding of their operation. This work investigated the effects of the disparate semiconducting properties, of electronic and statistical noise, and the effects of the above on the pulse height spectra and efficiency on BC layers that are almost an order of magnitude thicker than previously tested. Excellent diode characteristics with low reverse bias current and much higher breakdown voltages facilitate sensitive neutron detection.

The lightly doped BC layer is fully depleted, even at zero bias and operation at zero bias is feasible, albeit with somewhat reduced efficiency. Increased bias voltages lead to increased charge collection, shifting the peak in the pulse height spectra to higher channel number. At low bias, the effects of increased time constant are most pronounced, due to the short depletion width on the Si side and the low mobility of charge carriers in BC. This effect of significantly enhanced efficiency with a longer time constant is the strongest evidence to date of charge collection occurring in the BC layer. If charge collection were occurring only in Si, increasing the time constant would have no effect because the charge pulse rise time in Si is <20 ns. Neutron detection signatures from both the n-doped Si side and the p-doped BC side have been observed and the observed spectra from the BC side are consistent with the incomplete charge capture that we deduce from the behavior of the pulse height spectra with increasing time constant. A surprising feature is the significantly enhanced neutron detection efficiency for detection on the p-side of the junction, which we attribute to lower noise due to better grounding on the Si side.

The efficiency of neutron detection will be significantly improved by decreasing noise and increasing the charge collection fraction within the BC layer, a function of its semiconducting properties. Recent investigations of the effects of growth temperature, *in situ* annealing and *in situ* sputtering of the substrate are encouraging. Our data clearly show that even at this much lower charge collection efficiency, highly efficient neutron detection in all BC detectors is possible, provided the noise level is adequately low.

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